Cross-Pollination in Science and Technology: The Emergence of the Nanobio Subfield

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ABSTRACT

The emergence of new research based organizational fields drives both scientific progress and economic growth. Yet our knowledge of field emergence is limited. This paper shows how the cross-pollination of ideas between nanotechnology and biotechnology yielded a new subfield - nanobiotechnology. The growth of the nanobio subfield exceeds the growth within both nanotechnology and biotechnology. Drawing on a large dataset of publications, patents and press-releases between 1991 and 2005 we show that cross-pollination facilitates the movement of ideas between science, technology and commercialization. Scientists who reside in commercial firms additionally assist this transfer of ideas. The results point toward a growth dynamic where the translation of scientific ideas into technological possibilities facilitates subsequent commercialization, and where commercialization further spurs technological development.

INDUSTRIAL DEVELOPMENTS

The emergence of new commercial fields is a driver of economic growth (Ruttan 2001). The complexity of new products makes industrial developments increasingly dependent on advancements in science. Industry case studies on biotechnology (McKelvey 1996; Orsenigo 1990; Owen-Smith et al. 2002; Zucker and Darby 1996), chemical and electrical engineering (Kenney and Goe 2004; Mowery and Rosenberg 1998) semiconductor and laser (Klepper 2001), medical instruments (Trajtenberg 1989; 1990) illustrate how the discovery of natural properties enabled industrial developments. Academic and industry scientists often mediate commercializing their technology (Louis et al. 1989). A sign of the increasing importance of science in technological development is the sharp increase in the number and share of literature citations in patents (Narin and Olivastro, 1992; Narin, Hamilton and Olivastro, 1997), suggesting that inventors increasingly use directly inputs from published scientific research.

Knowledge. A key aspect of the development, growth and commercialization of a new subfield is the movement and cross-pollination of knowledge. In the post-industrial society knowledge has become the principal asset in nearly all productions, hence the availability and skills to generate and integrate knowledge within the organization determines its economic value (Elliasson 1996). In most modern products it is the knowledge incorporated in the product and not the production costs that primarily determines the market price of an object or a service (Ruttan 2001). An example is medicine. Most modern medicine has low production costs but a high market value; it is the knowledge integrated in the product and the inability of others to reproduce it that determines the value of the product. The competitive advantage gained by a knowledge increase can be retained either through intellectual property rights or by the inability of competitors to reverse engineer the product (Granstrand 2004).

There is disagreement within the literature about how to conceptualize and measure knowledge. Cohen and Levinthal (1990) focus on R&D spending, Zander and Kogut (1995) emphasize procedural knowledge and Boisot (1998) suggest the role of encoded knowledge. For this paper we suggest that the industrial dynamics of knowledge creation is best analyzed by investigating the movement of the most basic component of knowledge; the idea.

Ideas involved in the commercialization of knowledge exist in three integrated but separate institutional environments: science, technology and commerce. In science researchers generate scientific knowledge, which they disseminate through scientific articles, presentations at research conferences and their informal network of friends and colleagues. Some scientific ideas are translated into technological ideas in the form of technical drawings, documentation and patents. A fraction of these technological ideas are subsequently integrated into actually products; they are commercialized (Agrawal 2006). The literature often assumes that technological ideas and commercialization are identical phenomena, measured by whether a scientific idea is paralleled with a patent (Murray 2002). There is however evidence that even though a scientific idea is translated into a technological possibility in the form of a patent it is not always commercialized (Mirowski and Sent, 2002). Research on the commercialization of knowledge has increased over the last decade, but we still lack understanding of how and why ideas move between knowledge spaces. In particular research is missing on how the movement of ideas impacts the overall development of a field (Aldrich 1999). The research question that we address in this paper is thus: *How does the movement of ideas between the science, technology and commercialization influence the development of a subfield?*

Cross-pollination. Studies of science and technology show that radical innovations spurs the emergence of new fields (Basalla 1988). The development of genetic engineering for example enabled the emergence of the biotechnology industry (Powell, Koput and Smith-Doerr 1996; Zucker, Darby and Brewer 1998). Characteristic of most novel technological subfields is that they proliferate at the periphery of existing technological fields, brokering, cross-pollinating and recombining knowledge from separate technological areas (Hargadon and Sutton 1997; Hargadon 2003). Over time they grow large and become separate fields. Biotechnology for example emerged at the intersection of biology and organic chemistry. The collaboration of people in multiple disciplines enabled the discovery of DNA as a double helix. Rosalind Franklin and her collaborator Maurice Wilkins were educated as chemists, James Watson had a degree in zoology, and Francis Crick had a degree in physics (Stokes 1982). The later development of molecular biology and its commercialization in the form of biotechnology drew attendance from people both in chemistry, biology and physics. Digital sound, which emerged at the intersection between computer science and music, is another example of a new interdisciplinary subfield. It was only through the availability of persons with connections both within the computer science and the music department that the first digital synthesizer was developed. Digital sound is now a key element in the multibillion dollar music industry (Nelson 2005).

We thus hypothesize (figure 1 depicts the hypotheses):

Hypothesis 1a: If an idea appears in a science article that contains ideas from two different scientific disciplines then the idea is more likely to subsequent become part of a technology

Hypothesis 1b: If an idea appears in a science article that contains ideas from two different scientific disciplines then the idea is more likely to subsequently be commercialized

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Figure 1 about here

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Proximity. For ideas to flow from one sphere to the other they need to be translated and integrated to fit the social structures and prescriptions characteristic of the receiving sphere (Bechky 2003). The process of translating ideas between spheres is make easier if individuals involved in the translation process possess knowledge from both spheres. In the process of science commercialization the availability of individuals who are familiar with both the science and commercial space will facilitate the translation of ideas from the science sphere into the technological sphere. We thus hypothesize:

H2a: If an author affiliated with a private company presents an idea in a scientific article then the idea has a higher probability of subsequently being incorporated into a technology

H2b: If an author affiliated with a private company uses a keyword within a technology then the keyword has a higher probability to be commercialized

Impact of technology translation. The process of translating an idea from the science space into the commercial space is intersected by the technology space. Once detailed descriptions of how a scientific idea might be commercialized is outlined in the technology space then it is easier for that idea to subsequently be adopted and integrated into the commercial sphere. We thus hypothesize:

H3: If an idea appears in a patent then it will subsequently have a higher likelihood of commercialization.

Feedback effects. Innovation researchers have heavily criticized the linear model of innovation, which assumes that ideas flow only in the direction from science to commerce

(Kline and Rosenberg 1986; Mowery and Sampat 2005). Rosenberg (1982) shows that technological commercialization has a large impact on both scientific and technological developments. The commercial advances in aviation in the beginning of the 20th century for example led to an explosion in the knowledge of aerodynamics. The integration of an idea into a commercial product stimulates knowledge creation within this technological area. This will lead to subsequent increases of the use of the idea within the technological space. An example of the increased integration of a specific idea into a technological product following commercialization is cellular telecommunication. When the first cell phone was invented it was not considered to have a great economic potential. In the beginning the inventors only imagined that people in the military might benefit from the technology. As the technology was made commercially available it, however, became apparent that the demand for the technology was much larger than the inventors had originally anticipated. This demand for the product spurred further technological developments (Simard 2004). We thus hypothesize:

Hp4: The more common the use of an idea is within the commercial space at a given time the greater the subsequent use of this idea will be within the technology space

DATA AND METHODS

Setting: Nanobiotechnology

We will test our hypotheses within the subfield of nanobiotechnology. We chose to study the emergence of the nanobio subfield, since it is an emerging interdisciplinary field at the intersection of two technological areas; biotechnology and nanotechnology. Through interviews with nanoscientists we identified nanobio as a subfield of increasing importance. Nanotechnology emerged out of the intersection between material science, electrical engineering and physics in the beginning of the 1980s. The invention of new methods of inventing like the atomic force microscope (Darby and Zucker 2003) enabled novel research at the nano-scale. Biotechnology is a more established discipline that emerged at the intersection between biology and organic chemistry in the middle of the 1970s.

In the early days of nanotechnology, biotechnological science and technology was a marginal application area. During the 1990s the synergies between biological-sciences and nano-sciences started to emerge and has been growing dramatically since. There is evidence that a commercial nanobio field is in the making, both due to extraordinary scientific achievements and the existence of entrepreneurial firms attempting to commercialize nanobio science (Darby and Zucker 2003). The core element that delineates the nanobio field from nanotechnology and biotechnology is that it combines biological structures with inorganic molecules. Discoveries within nanobio address diagnostics, drug development and drug delivery. Many scientists and companies are working to create “lab-on-a-chip”, which can be used both for drug discovery and drug delivery. In an interview with a scientist in material science he explained that during most of his career he had researched nanoparticles, which ultimately improved disk drive performance by making them more reliable, faster and smaller. Over the last couple of years he collaborated with researchers in molecular biology to develop better methods for diagnosing diseases. They would combine the knowledge of nanoparticles that he had developed through his work in disk drives with the molecular biologists knowledge about genes, proteins, and enzymes to develop new tools that would be able to tell whether a person was suffering from a specific kind of cancer or not. This combination of knowledge let to rates of improvement over the existing technology that far exceeded the rates of improvement that he was used to generating within disk drives. Other scientists are taking advantages of the novel properties of nanoparticles to develop methods for drug delivery, like encapsulating a drug within a nanoparticle attach with receptor so that it will join with for example a cancer tumor and deliver the drug more precisely. This will enable patients to experience fewer side effects and for physicians to administer higher doses, which increase patients benefits from the treatment.

We chose to study the emergence of the nano-bio subfield exclusively in the United States, since the high prominence of United States as the locus of innovation within this area is widely recognized (Hall and Trajtenberg 2004). Moreover many important non-American inventions tend to be published and patented in the United States due to the importance of the American commercial and knowledge market (Huang et al. 2003). By the end of 2004 in there were 12.256 biotechnology patents filed within the European Patent Office versus 43.410 by the US Patent and Trademark Office. With regards to nanotechnology patents there were only 958 patents filed by the European Patent Office versus 4.828 by the USPTO.[2]

Methodological motivation

Patents may be based not only on the prior art documented in other patents, but in part or fully on new scientific knowledge. Since published scientific research results can be used to illustrate the state of the art against which the application has to be evaluated, patent examiners will search for relevant references in the scientific literature. The logic of these references is to document the material that is held against the application. Researchers have used these metrics to develop a taxonomy of industries (Grupp 1992; Heinze and Schmoch 2004; Tijssen 2004) and to track networks of patent citations (Popp 2005; Verspagen 2005). The theoretical motivation for tracing back the full ramification of citations from more recent patents to historical is to give insights on the underlying dynamics of knowledge.

On the methodological side, several shortcomings of the existing measures of non-patent literature should be recognized. First of all, non-patent literature citations suffer from an important limitation: it is not clear to what extent they are assigned by inventors or by examiners. It is well known that inventors primarily introduce references in the USPTO, while

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[2] For a definition of a biotechnological and nanotechnological patent see in section 0.

in the European system they are introduced exclusively by the examiners. Breschi and Lissoni (2004) claimed that, at least in the US patent system – since people quote US references for reasons of availability and for different purposes - there is a severe distortion in the interpretation of data. The full validity of information on cited patents has to be established, given that the motivations for a patent to cite another patents are rather intricate and call upon legal and strategic considerations. Thus we face both measurement and validity issues.

Second, non-patent citations do not convey any information on the degree to which the scientific content was able to generate valuable innovation. Since we know that the distribution of patents by degree of usefulness is extremely skewed, it is possible that patents with a high number of non-patent references are among those that are never used, and so have limited economic value. One approach to mitigate this limitation is given by a careful analysis of patent quality, using the indicators proposed in the literature initiated by Trajtenberg (1989, 1990) and fully developed by Jaffe, Trajtenberg and Henderson (1993).[3] There is sufficient evidence in the literature that the economic value of patents is associated with the number and quality of citations received in other patents (Hall, Jaffe and Trajtenberg 2005; Harhoff et al. 1999; Jaffe and Trajtenberg 2002). (Harhoff, Scherer and Vopel 2003; Lanjouw and Schankerman 2001) have suggested a different metrics, i.e. the existence of litigation for patents, implying that patents for which assignees are willing to pay for defense against infringement, have larger economic value.

In this study we address the science and technology interaction using a novel approach. We measure how scientific concepts move between three social arenas: Science, technology and commercialization. The proxy we use to measure this knowledge transfer is the presence of keywords in three document types produced by institutional actors: Scientific articles, patents, and press releases representing the aforementioned three social arenas.

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[3] For a survey of the literature see Jaffe and Trajtenberg (2000)

Science

We used the ISI database to locate keywords used in nanotechnology and biotechnology science in the 14-year period between 1991 and 2005. Due to the difference in age between the biotechnology and the nanotechnology field we used two different methods to isolate biotechnology and nanotechnology keywords.

Biotechnology keywords. To single out the nanobio science field we identified scientific publications that contained both biotechnological and nanotechnological search words. We selected author specified keywords from two specialized journals in the field of Biotechnology and Applied Microbiology and Cell Biology, respectively *Biotechnology and Bioengineering* (BB) and *Embo Journal* (EMBO). Our criteria for selecting these journals were the following: First, we looked for journals there were widely read in the field: both BB and EMBO has been at top quartile of the impact factor index distribution of their subfield since at least 1999 (ISI JCR, 2005). Secondly, we looked for journals founded before 1991 and regularly containing authors' keywords: in ISI authors' keywords started to be collected regularly since January 1991. Finally, we looked for journals that were targeted to broad topics within the field and published many articles in absolute terms. We isolated all keywords used in BB and EMBO in the period 1991-2005 obtaining a combined list of 28,194 biotechnology keywords[4].

Nanotechnology keywords. Since there are no established nanotechnology journals that have been around for a long time we had to use a different search strategy to isolate nanotechnology articles. To identify nanotechnology publications we used a list of keywords - defined by the ISI Fraunhofer Institute and published by (Nyons and et al 2003) - to search titles, keywords and abstracts to identify nanotechnology articles. This search strategy enables us to retrieve a database of more than 240,000 publications from ISI for the period 1991-2004.

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[4] 1153 keywords overlapped between the two journals.

From this set of articles, we retrieved all of their keywords, which provided us with a basic pool of nanotechnology keywords constituted by 146,484 words.

Nanobio publications. To isolate nano-bio keywords we looked at the overlap between the biotechnology and the nanotechnology keywords. This provided us with a list of 7,715 nanobio keywords.

Technology

In the following analysis we selected data from USPTO. [5] Given the important role of the United States as a locus of technical change in the last decades, we think that this limitation to U.S. patenting activity does not constitute a serious drawback for a preliminary investigation of this kind.

Due concerns for endogeneity we cannot use the same search words to isolate nano-bio patents that we used to isolate nano-bio articles. To delineate a nano-biotechnology field we followed two different search strategies according to two different knowledge constructs within the field. In the first search we isolate patents through a static process. We use the nanobio search words identified by (Fraunhofer-ISI 2002)[6] listed in table 4. We searched for patents that had any of the search words in either the titles or abstracts during the period 1971-2004. We obtained a dataset of 1.491 patents in that period. Characteristic of these patents is that they involve a specific technique or compound that is unique to nano-bio and is found neither within nanotechnology or biotechnology.

The second search strategy that we employed isolated innovations that contained a combination of knowledge coming from the biotechnology field and the nanotechnology field,

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[5] The source of data is constituted by the Delphion patent database (DPD), which is an on-line proprietary database, accessible from www.delphion.com. It includes data from different national Patents Offices. In particular, it offers a complete text and images of all patents issued by the US Patent and Trademark Office (USPTO) since 1971.

[6] In order to circumvent the problem of an accidental selection of keywords given by experts, they listed all terms in the patent database beginning with “nano”. An expert in the NST assessed for each term whether it is used in the context of nanotechnology and whether it indicates an unambiguous relation to this field. 40 keywords queries have been obtained, identifying singularly a field. See appendix 1 for more information.

showing the cross pollination of these two streams of science. To isolate these patents we looked at the overlap between nanotechnology and biotechnology patents. Patenting propensity in the biological related fields is widely recognized in the literature and in the press (Arora and Gambardella 1994; Gambardella 1995). The US Patent and trademark office have for many years had specific patent classifications for biotechnology innovations. We use the IPC based strategy used by Schmoch (2003) to identify biotechnology patents, and search the USPTO database in the period 1971-2004. This search generated a dataset of 43.310 patents. Figure 1 depicts the exponential growth in the patenting activity within the biotechnology field.

The search strategy for nanotechnology patents had to be mainly based on keywords, since the specific IPC-subclass B82B for this field was introduced in the year 2004 (Commerce 2004) and does not cover former years. We used a keyword search strategy suggested by Fraunhofer ISI Institute in Karlsruhe, which we found to be the most complete and validated by experts among the static keywords methodologies. Articles and reports have already been published using this search methodology (Smoch et al 2002; Bonaccorsi and Thoma, 2005).

We performed the search in the titles and the abstracts of the patents, and obtained a sample of 4.828 patents granted before May 2004. The nanotechnology patents, like the biotechnology patents, grow exponentially, especially in the last years (1996-2002). The USPTO has patented several thousands of inventions in nanotechnology, with around 4.500 patents filed in 2003.

To isolate the nano-bio patents corresponding to the second knowledge combination we identified the overlap between the datasets of nanotechnology and biotechnology patents. This resulted in a sample 406 patents over the period. We then combined the two datasets that we had obtained using the different search methodologies to obtain a complete sample of the nano-bio space. This yielded a total of 1.573 patents. The first patent in the field was granted in the 1975, but only during in the 1990s does the growth in nano-bio patenting really take off.

Commercialization

The commercialisation of a scientific and technological idea takes place very often in the form of proliferation of new products. We tracked the commercialization of ideas by retrieving the company press released - newswires - in the Lexis-Nexis database over the period 1980-2005.[7] Our search strategy was two fold. The first has been based on the same nano-bio keywords that we used for patents, obtaining a sample of around 2,307 news events. Secondly we considered the events that have been self-classified by the announcing firms to concern the biotechnology and the nanotechnology industry. Indeed the newswire contain not only a detailed description on the new product characteristic but also information on the industry, location, company background and people involved. The second search strategy yield an output of 730 press releases. We combined the two search strategies, obtaining 2837 press releases.

OPERALIZATION AND MEASURES

The unit of analysis used in this paper is ideas measured as keywords in a given year. We analyze how scientific ideas move between three institutional areas: Science, technology and commercialization represented by scientific articles, patents, and press releases.

We considered in the analysis only the *authors' keywords*, which are those that are self-revealed by authors in scientific publications. ISI started to collect keywords in 1991, which is the reason that our analysis starts in that year. In the sample we excluded the

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[7] The Lexis-Nexis newswire database delivers full-text, unedited news releases as written by the originators. The releases cover a broad range of topics including quarterly and annual earnings, dividends, earnings forecasts, new stock issues, debt financing, mergers and acquisitions, antitrust actions, tender offers, new products and production statistics, executive appointments and resignations and reactions to government regulations or court decisions.

keywords that are composed by less than four letters, reducing hence the probability of having the synonymous matched keywords. We isolated 140,073 nanotechnological and biotechnological keywords over the period 1991-2004, as we defined before. We tracked the occurrence of these keywords in scientific publications over the period 1991-2004, having a not balanced panel of 249,086 observations.

Dependent variables. To test out hypothesis we develop the following variables. TECH: Measures the extent to which a scientific ideas is integrated as part of a technology. Tech is a binary variable with a positive value if a keyword appears in a nanobio patent (title, abstract, or claims) the year after publication using that keyword in science. COM: Measures the extent to which an idea has been commercialized. Com is a binary variable with a positive value if a keyword appears in a nanobio newswire in title or body in the year after a publication uses that keyword in science.

Independent variables: CROSS: Measures the cross-pollination effect. It is a binary variable, which takes on a positive value in case an article contains both nanotechnological and biotechnological keywords. PROX: Measures the "proximity argument". It is a count variable, which measures the number keyword occurrences in an article where the author is affiliated with a private company.

Control variables. LENGTH: Measures the length of a keyword. It is a count variable, given by the number of letters. ABS_USE: Measures the diffusion of a keyword in science. It is a count variable, given by the number of occurrences of a keyword in sciences in a given year. INTER: Measures the interdisciplinary effect and controls for journal effects. It is a count variable, constituted by the mean number of sub-fields in which a keyword appears according to the ISI journal citation report subject categories.

Table 1 depicts the correlation between the variables. The highest correlated variables are TECH and COM with a correlation coefficient of 0.33. This high correlation is not surprising given that if an idea has already been incorporated into a patent then the idea is also likely to later be commercialized. The correlation between INTER and CROSS is only 0.018 pointing to the fact that cross-pollination and interdisciplinary are two different measures. CROSS is measured at the level of the individual article whereas INTER is derived from ISI categorizations of the journal.

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Table 1 about here

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EMPERICAL RESULTS

Growth of the subfield

Scientific developments. Since the early 1990s nanotechnology has undergone a dramatic development. Figure 2 shows the growth in nanotechnology and nanobio with 1991 as the base year. To create the graph we divided the stock of publications in a given year by the stock of publications in 1991 to compare the growth in the general nanotechnology field to the growth of nanobio. Nanotechnology has undergone an exponential growth in the number of nanotechnology publications, but the growth rate for the nanobio field has been higher than the growth rate for the nanotechnology field. Figure 2 shows that during the period 1991 to 2003 the nanobio field grew from constituting 1/7 to 1/3 of the overall nanoscience field. The growth rate of nanobio was thus significantly higher than the overall growth in nanotechnology.

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Figure 2 and 3 about here

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Technology developments. The rapid growth of nanobio science is paralleled within nanobio technology. Figure 4 depicts the dynamics of biotechnology, nanotechnology and nanobio over time. Both nanotechnology and biotechnology have experienced an exponential growth in the production of patents during the 1990s and early 2000s. The growth rate within the nanobio field is however much higher than in its two parent fields. Whereas the stock of biotechnology patents has risen nearly 9 times from 1990 to 2004, and the stock of nanotechnology patents had risen nearly 15 times from 1990 to 2004 then the stock of nanobio patents has risen an extraordinary 54 times from 1990 to 2004.

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Figure 4 about here

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Commercialization development. Figure 4 illustrates the growth in press releases containing nanobio ideas from the first press release from 1991 to 2005. During the 1980s there was a slow growth within nanobio commercialization and it was not until 1990 that the commercialization of nanobio really escalated. Another dramatic increase in the amount of nanobio press releases happened around year 2000 after which date hundreds of nanobio announcements were released every year.

Determinants of Growth

We used a probit model for the estimation of the stated hypothesis. The results are found in table 3 and table 4.

Hypothesis 1a and 1b. We find support for hypothesis 1a and 1b. If an idea appears together with ideas pertaining to both nanotechnology and biotechnology then the idea has a higher likelihood to both later be integrated into a technology and to later be commercialized. This result supports our hypothesis that cross-pollination between ideas from different disciplines creates novel ideas that are more likely to posses commercial benefits. Interestingly this positive effect of the cross-pollination does not occur when looking only at the rough measure of whether an idea was published in a journal that spans multiple disciplines. Publication of the idea in an interdisciplinary journal actually negative impacts the possibility that the idea will later be commercialized.

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Table 2 and 3 about here

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Hypothesis 2a and 2b. We find support for hypothesis 2a and 2b at the 1% significance level. If a person affiliated with a private company presents an idea in a scientific article then the idea has a higher likelihood of subsequently being incorporated into a technology and of being commercialized.

The effect of proximity to market is much smaller than the effect of cross-pollination. If a keyword occurs in an article that contains nanotechnology and biotechnology ideas then the likelihood that it will be incorporated in a patent is 6% higher than if no cross-pollination occurs. If an author is affiliated with a private company the likelihood that the idea will be translated into a technology is only 0.3% higher than if all the authors are scientists. The highest marginal effect is the impact of cross-pollination on the commercialization of the idea. If an idea is published in an article that contains both nanotechnology and biotechnology ideas then the likelihood that it will later be commercialized is 7% higher than if no cross-pollination occurs, whereas the effect of the industrial affiliation of one of the authors is only 0.4%.

We further find an interesting interaction effect between CROSS and PROX, which is significant at the 1% level for the probability that an idea will be commercialized, but insignificant for the probability that the idea will be incorporated into a technology. This interaction effect has negative coefficients, which indicate that the positive effect of cross-pollination between nanotechnology and biotechnology for the probability that the idea will be commercialized only holds true if the authors are scientists. If the authors instead are affiliated with a private company the cross-pollination actually has a negative effect on the probability that an idea will be commercialized.

Hypothesis 3 and 4: We find support for hypothesis 3 at the 1% significance level. If an idea has already been incorporated into a technology it is 3% more likely that it will subsequently be commercialized. This effect is thus the second most powerful predictor of whether a scientific idea will be commercialized. We also find support for hypothesis 4 that if an idea has been commercialized then there is a higher likelihood that the idea will subsequently be incorporated into a technology. The result is significant at the 1 % significance level. This result demonstrates a reinforcing dynamic between the incorporation of an idea into a technology and its commercialization. But this feedback effect is not large. If an idea has been commercialized then it only increases the probability that it will again later be included in a technology with 0.05%.

General model: Overall the model has a lot of explanatory power, especially considering the limited number of variables included in the model. The model explains 17% of the variance with regards to whether an idea will be incorporated into a technology, and 24% of the variance with regards to whether an idea will subsequently be commercialized. These results show the strong predictive value of the movement of ideas between science, technology and commercialization.

DISCUSSION

The growth of new industries and commercial fields is central to the sustainability of economic growth within a modern society (Arora, Landau and Rosenberg 1998; Rosenberg 1998). Chemical engineering has for example spurred from the oil and petroleum refining and dyes industries during the late 19th century. Indeed, the benefits in the overall economic growth were substantial and were unfolded for many decades after that discovery.

In this paper we show that a new subfield is emerging at the intersection between nanotechnology and biotechnology. This subfield is growing more rapidly than its two parent fields nanotechnology and biotechnology. Our results show that the success of the subfield is partly driven by a cross-pollination of knowledge between nanotechnology and biotechnology, since ideas that are part of scientific articles that contain aspects of both nanotechnology and biotechnology have a higher likelihood of later being incorporated into technology and subsequently be commercialized. Studies have addressed whether the cross-pollination of knowledge generates more creative ideas and concepts (Hargadon and Sutton 1997; Hargadon 2003). We, however, show that the cross-pollination of knowledge also contributes to a higher likelihood that the ideas will be commercialized.

We further show that the translation of scientific ideas into technology is aided when persons with industrial affiliation present scientific ideas. There has been debate about the role scientists with industrial affiliation play in the translation of knowledge between science and technology. Some researchers have claimed that industrial scientists only publish their knowledge in scientific journals if is it something that does not have commercial value (Bird, Hayward and Allen 1993). The argument behind this claim is that companies are reluctant to share any information that might provide their competitors with increased knowledge. Companies might thus choose to only publish information that is basic research, and thus far away from commercial possibilities. Our results counter this hypothesis. The ideas presented by industrial affiliates have a larger chance of subsequent presentation as a technological possibility. Companies thus present ideas within scientific articles that contain commercial value.

Studies have found research conducted by or in collaboration with industrial partners is less innovative than research done purely for the sake of science. Evans (2004) shows that industrial partners and industrial funding decreases the innovativeness of plant biotechnology research. Within the nanobio subfield industrial affiliates also display conservatism in their publishing efforts. First industrial affiliates have a higher tendency than university scientists to include ideas in their publication that are common. Second the strong positive effect on commercialization of cross-pollinating ideas from nanotechnology and biotechnology is reversed for industrial affiliates. If an idea is published together with a person that works in a private company cross-pollination diminishes the probability that the idea will be commercialized. This points to conservatisms among the industrial affiliates, since they are not engaged in commercializing innovative cross-pollinated ideas.

The relationship between the growth in scientific idea, technological possibilities and commercialization has been the subject of debate (Poole and Moore 2002). Our research shows not only that the cross-pollination of ideas in science facilitates the translation of ideas into technologies and commercial products, but that this translation process aids future commercialization. Combined with the finding that the commercialization of ideas stimulate the use of these ideas within technologies these results point toward a growth dynamic. The elements of this growth dynamic are that the cross-pollination of knowledge between two different scientific fields yields highly innovative ideas that are more readily translated into a technology. This translation then further facilitates subsequent commercialization. The last part of the dynamic is that commercialization feedbacks and spurs technological development.

Future research might address the effect that the integration of an idea into a technology and the commercialization of an idea have on the development within science. In particular the direction might be that of disentangling the existence and the intensity of the feedback reinforcing processes of technological and industrial developments onto scientific production.

Many scholars have criticized the linear model of innovation, which only describes a movement of ideas from science to technology and subsequently to commercialization, but not the reverse knowledge flow (Kline and Rosenberg 1986; Mowery and Sampat 2005). Rosenberg (1982) has provided in-depth historical accounts of how industrial development aids the growth of science, by both providing scientists with results unexplainable by existing scientific theories, and by developing tools that facilitates data collection. This important dynamic relationship between science and technology has however not been tested on a large empirical dataset.

TABLE AND FIGURES

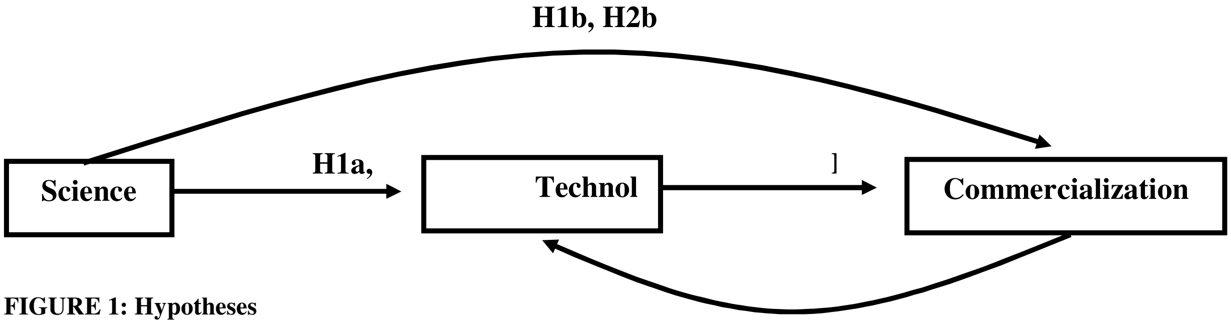


FIGURE 1: Hypotheses

TABLE 1 Correlation matrix among the explanatory and control variables

	TECH	COM	CROSS	INTER	PROX	LENGTH	ABS_USE
TECH	1.000						
COM	0.328	1.000					
CROSS	0.072	0.041	1.000				
INTER	0.002°	0.005	0.018	1.000			
PROX	0.055	0.042	0.071	0.008	1.000		
LENGTH	-0.098	-0.094	-0.102	-0.008	-0.042	1.000	
ABS_USE	0.067	0.055	0.152	0.002°	0.726	-0.056	1.000

Notes: All the correlations are significant at 1% level with the exception of those labeled by °

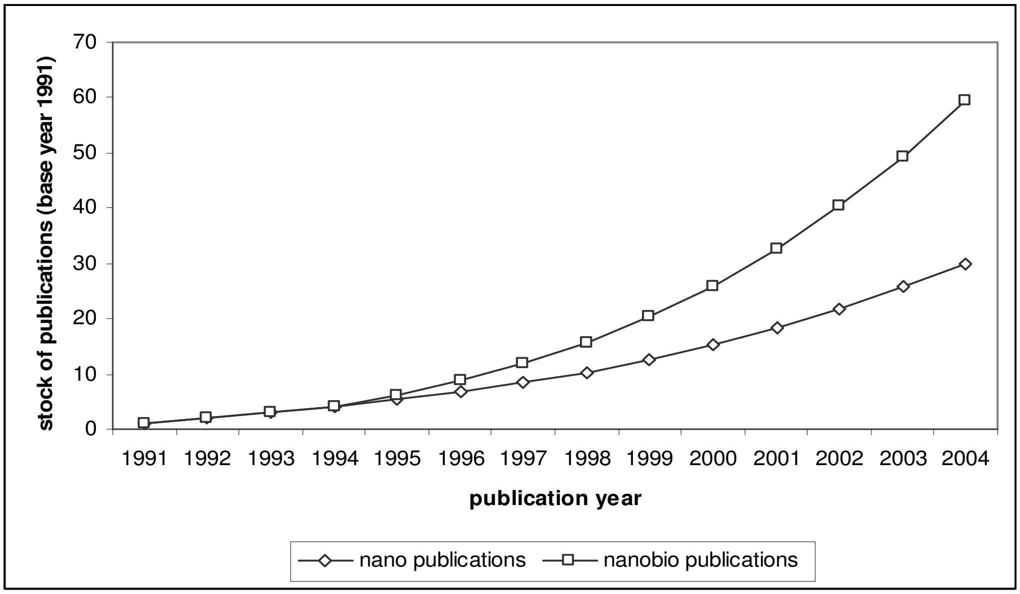


FIGURE 2: Cumulative Entry of Nano and Nanobio Publications (base year 1991)

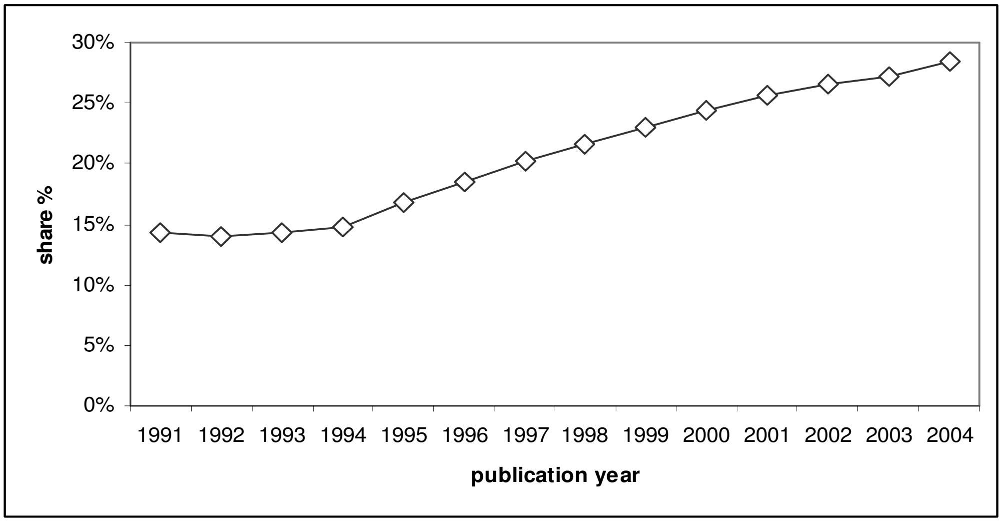


FIGURE 3: Importance of Nanobio subfield within Nano Science

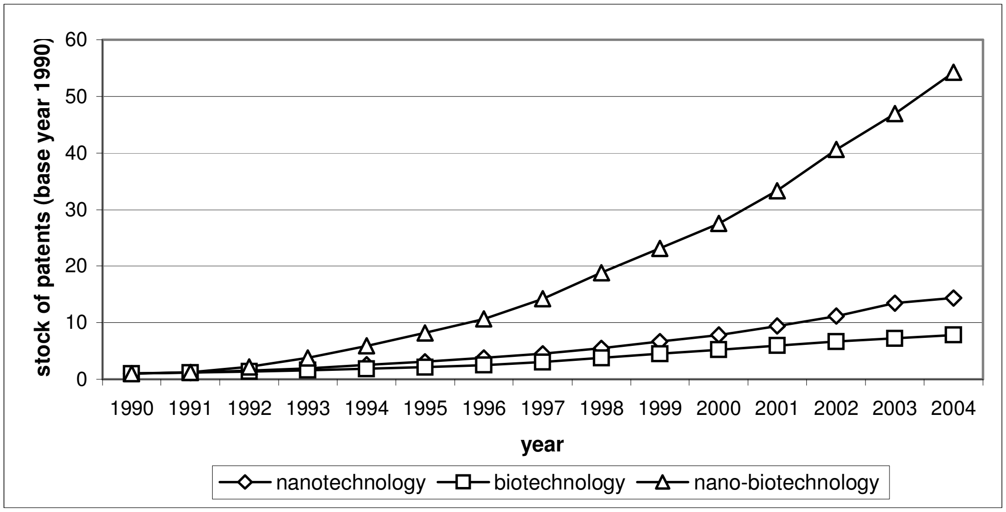


FIGURE 4: Nano – Biotechnology patents over time base year 1990

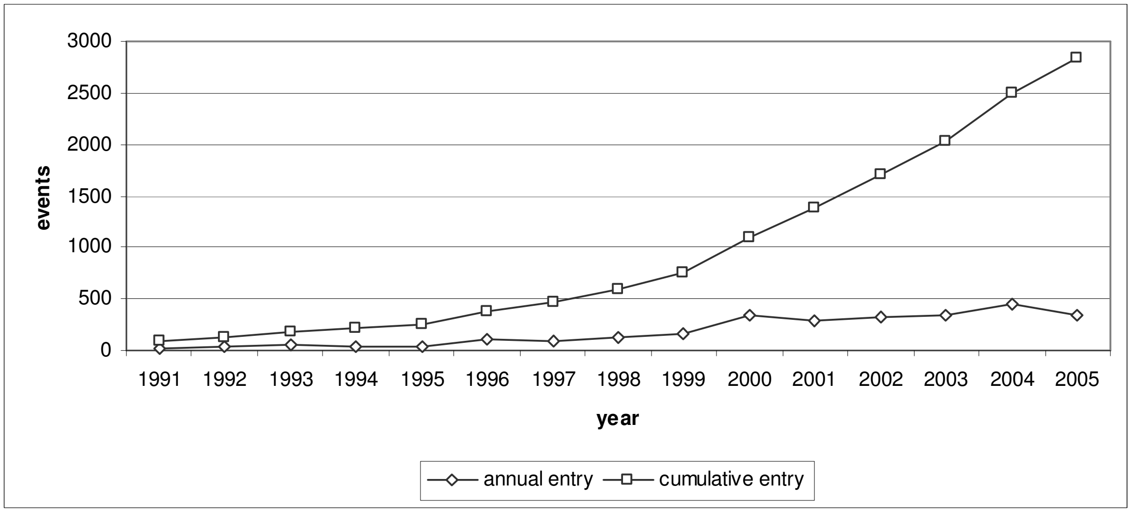


FIGURE 5: Nano – Biotechnology news-events over time

Notes: The events of 2005 regard only those announced in the first 9 months of the year.

TABLE 2: Probit estimations of the determinants of the keyword occurrence nanobio patents

	MODEL 1			MODEL 2			MODEL 3		
	Coeff.	std	sign	Coeff.	std	sign	Coeff.	std	sign
CROSS	0.81	0.02	***	0.63	0.02	***	0.67	0.02	***
PROX	0.08	0	***	0.05	0.01	***	0.06	0.01	***
COM	0.01	0	***	0.01	0	***	0.01	0.00	***
CROSS*PROX							-0.07	0.01	***
INTER	-0.01	0.01		-0.02	0.01	**	-0.02	0.01	**
LENGTH				-0.07	0	***	-0.07	0.00	***
ABS-USE				0	0	***	0.01	0.00	***
COSTANT	-1.83	0.01	***	-0.77	0.02	***	-0.78	0.02	
Number of obs	249086			249086			249086		
Pseudo R2	7%			16%			17%		

Notes: *** 1% level significance; ** 5% level significance; * 10% level significance

TABLE 3: Probit estimations of the determinants of the keyword occurrence nanobio newswires

	MODEL 1			MODEL 2			MODEL 3		
	Coeff.	std	sign	Coeff.	std	sign	Coeff.	std	sign
CROSS	0.75	0.02	***	0.56	0.02	***	0.59	0.02	***
PROX	0.12	0	***	0.04	0.01	***	0.05	0.01	***
TECH	0.52	0.01	***	0.39	0.01	***	0.39	0.01	***
CROSS*PROX							-0.05	0.01	***
INTER	0.05	0.01	***	0.06	0.01	***	0.06	0.01	***
LENGTH				-0.07	0	***	-0.07	0	***
ABS-USE				0.01	0	***	0.01	0	***
COSTANT	-1.79	0.01	***	-0.7	0.02	***	-0.71	0.02	***
Number of obs	249086			249086			249086		
Pseudo R2	15%			24%			24%		

Notes: *** 1% level significance; ** 5% level significance; * 10% level significance

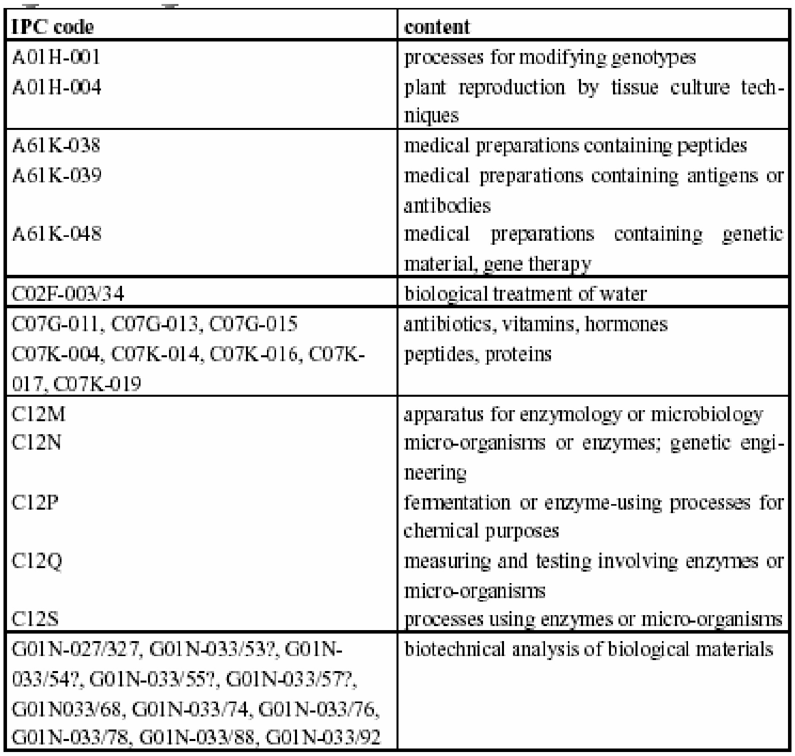
TABLE 4 Marginal effects of Model 2 in Patents and Newswires

	Patents	Newswires
CROSS	6.01%	6.97%
PROX	0.30%	0.37%
COM	0.05%	
TECH		2.86%
CROSS*PROX	-0.31%	-0.37%
INTER	-0.07%	0.41%
LENGTH	-0.34%	-0.54%
ABS-USE	0.03%	0.09%

Note: all the marginal effects are significant at 1% level.

APPENDIX

Table 2 Definition of Biotechnology Patents



IPC code	content
A01H-001	processes for modifying genotypes
A01H-004	plant reproduction by tissue culture techniques
A61K-038	medical preparations containing peptides
A61K-039	medical preparations containing antigens or antibodies
A61K-048	medical preparations containing genetic material, gene therapy
C02F-003/34	biological treatment of water
C07G-011, C07G-013, C07G-015	antibiotics, vitamins, hormones
C07K-004, C07K-014, C07K-016, C07K-017, C07K-019	peptides, proteins
C12M	apparatus for enzymology or microbiology
C12N	micro-organisms or enzymes; genetic engineering
C12P	fermentation or enzyme-using processes for chemical purposes
C12Q	measuring and testing involving enzymes or micro-organisms
C12S	processes using enzymes or micro-organisms
G01N-027/327, G01N-033/53?, G01N-033/54?, G01N-033/55?, G01N-033/57?, G01N033/68, G01N-033/74, G01N-033/76, G01N-033/78, G01N-033/88, G01N-033/92	biotechnical analysis of biological materials

Source: (Schmoch 2003) Fraunhofer ISI, Karlsruhe, Germany

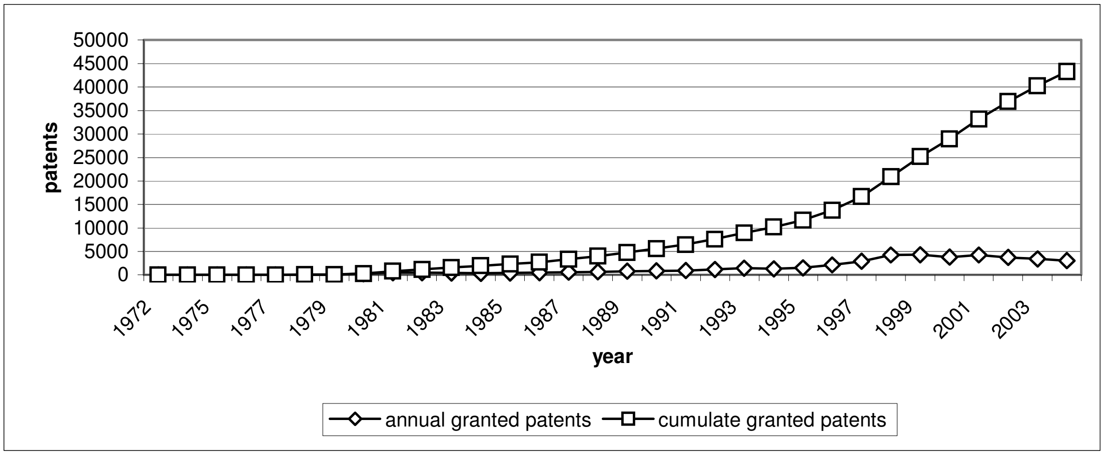


Figure 1 Entry of patents in biotechnology by publication year

Source: USPTO

Table 3 Keywords based search strategy for nano bio patents

```
S (BIOCHIP OR BIOSENSOR) AND (A61# OR G01N OR C12Q)/IC
S DNA(W)CMOS
S (BACTERIORHODOPSIN OR BIOPOLYMER# OR BIOMOLECULE#)AND (G11# OR G02# OR
G03# OR G06#)/IC
S BIOMOLECULAR TEMPLAT? OR VIRUS(2A)ENCAPSULATION OR MODIFIED VIRUS
S NANO? AND IMPLANT?
S (PATTERN? OR ORGANIZED) AND (BIOCOMPATABILITY OR BLOODCOMPATABILITY OR
BLOOD COMPATABILITY OR CELL SEEDING OR CELLSEEDING OR CELL THERAPY OR
TISSUE REPAIR OR EXTRACELLULAR MATRIX OR TISSUE ENGINEERING OR BIOSENSOR# OR
IMMUNOSENSOR# OR BIOCHIP OR CELL ADHESION)
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